# Atomic-Scale Friction in Xe/Ag and $N_2/Pb^1$

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# ABSTRACT

Quartz crystal microbalance (QCM) and electrical resistivity measurements were carried out on the systems Xe/Ag and  $N_2/Pb$  to determine the relative contributions of electronic and phonon dissipative mechanisms to sliding friction. Results show significantly differing proportions of electronic friction in the two systems.

KEY WORDS: electrical resistivity, lead, nanotribology, quartz microbalance, silver, superconductivity, xenon

#### 1. INTRODUCTION

The fundamental origins of friction, an important physical phenomenon in light of both its everyday familiarity and its enormous economic impact, have been discussed and debated for at least 300 years, with very little resolved [1]. With the advent of new experimental techniques capable of studying the force of friction which results when a finite number of atoms is made to slide on a crystalline substrate, a new field involving investigations at atomic length and/or time scales (nanotribology) has evolved [2, 3] allowing frictional dissipative mechanisms to be probed for the first time [4].

At the atomic scale, friction is believed to originate primarily via sliding induced excitation of atomic lattice vibrations (phonons) [1], whose lifetimes are on the order of  $10^{-9} - 10^{-12}$ s. Electronic contributions to the energy dissipation (attributed to conduction electron scattering from surface impurities) have also been suggested as significant contributors to frictional energy losses, if conducting interfaces are involved [5].

Definitive proof of electronic contributions to friction is of great interest, since to date the vast majority of fundamental theoretical treatments of friction have considered phonon contributions only [1]. A variety of practical applications become possible moreover, in cases where electronic contributions dominate. For example, for the case of adsorbed films or particles on metal substrates, the atoms could be dragged along the surface via electronic friction forces arising from a dc current. Qualitative evidence for the occurrence of electronic contributions to friction has been previously demonstrated for the case of ethane and ethylene films adsorbed on silver and chemisorbed oxygen surfaces [6]. Quantitative comparison with theory were difficult for those studies due to the fact that the structure of chemisorbed oxygen on silver is sensitively dependent on kinetic details [7].

Two experimental approaches to determine the relative contributions of electronic and phononic dissipative mechanisms to sliding friction in metallic interfaces involve (a) comparison of electrical resistivity data with that recorded via a quartz crystal microbalance (QCM) technique, and (b) QCM measurements of friction levels above and below the superconducting transition temperature of a metal substrate. We employed the first technique on the system Xe/Ag(111) and the second technique on the system  $N_2/Pb$  and report our observations here.

## 2. EXPERIMENTAL DETAILS

The quartz crystal microbalance (QCM) has been used for decades for microweighing purposes [8], and was adapted for friction measurements in 1986-88 by Widom and Krim [9, 10]. A QCM consists of a single crystal of quartz which oscillates in transverse shear motion with a quality factor Q near  $10^5$ . Adsorption onto the microbalance produces shifts in both the frequency  $f_o$  and the quality factor Q, which are indicative of the degree to which the adsorbate is able to track the oscillatory motion of the underlying substrate. Characteristic slip times  $\tau$ , and friction coefficients (i.e. shear stresses per unit velocity)  $\eta$ , are determined via the relations [9]:

$$\delta(Q^{-1}) = 4\pi\tau\delta f_o \qquad \eta = \frac{\rho_2}{\tau} \tag{1}$$

where  $\rho_2$  is the mass per unit area of the adsorbate. In terms of separate phonon and electron-hole slip times,  $\tau_{ph}$  and  $\tau_{eh}$ , the slip time  $\tau$  can ideally be written as

$$\frac{1}{\tau} = (\frac{1}{\tau_{ph}} + \frac{1}{\tau_{eh}}). \tag{2}$$

#### 3. RESISTIVITY MEASUREMENTS

One potential approach to determining the electronic contribution to the total sliding friction in a film-metal interface assumes that electrons in the metal substrate experience a drag force equal in magnitude to the force required to slide the adsorbed film [5]. The change in the metal film's resistivity  $\rho$  due to adsorption of the monolayer has been related to the electronic slip time  $\tau_{eh}$  via the expression [5]

$$\frac{1}{\tau_{eh}} = \frac{n^2 e^2}{M} t \frac{\Delta \rho}{\Delta n_a},\tag{3}$$

where n is the volume density of conduction electrons, e the electronic charge, M the mass of an adsorbate particle, t the metal film thickness and  $n_a$  the number of adsorbate particles per unit area. Values of  $\tau_{eh}$  for a range of chemisorbed and physisorbed systems have been tabulated in Ref. 5, with physisorbed systems characterized by  $\tau_{eh}$  in the range  $10^{-9}$ - $10^{-10}$  s. By comparing the value of  $\tau_{eh}$  determined from resistivity measurements with the value of  $\tau$  determined from QCM measurements, one can in principle determine the relative contributions of phonon and electron dissipative mechanisms to friction.

Data were recorded in equilibrium conditions for adsorption of Xe onto the surface of silver film electrodes which were evaporated in situ onto overtone polished quartz crystals ( $f_o = 8 \text{ MHz}$ ). The evaporation was carried out at room temperature with 99.999% pure Ag at a deposition rate of 0.05-0.1 nm/s. In the case of the resistivity measurements, a four-wire pattern was evaporated onto the quartz crystal surface. For QCM measurements, a silver electrode was evaporated onto each major face of the quartz crystal by rotating the sample between depositions. Samples were transferred within the vacuum system to a gas adsorption chamber where adsorption could be carried out at 77.4K.

Fig. 1 shows resistivity and QCM data for adsorption of Xe onto a 95 nm thick Ag film at 77.4K. The frequency shift data reflect the number of adsorbed particles per unit area. Each step in the isotherm corresponds to condensation of a monatomic solid

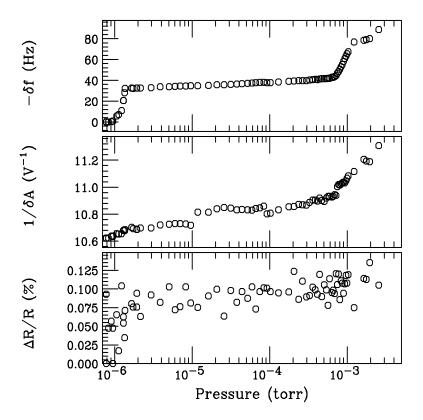


Figure 1: Frequency shift, inverse amplitude shift and resistance versus pressure for Xe/Ag at 77.4K.

layer of Xe, and the verticality of the steps is indicative of large ( $\approx 100$  nm) regions of substrate crystalline uniformity. The resistance data depicts the resistivity of the silver film increasing monotonically with the frequency shift, for coverages up to one monolayer, and achieving a saturation value beyond it. This behavior is consistent with resistivity measurements reported previously [11].

The calculated electronic and total slip times versus coverage for the fig. 1 data set are presented in fig. 2. Comparison of the slip times beyond the lowest coverages indicates that electronic friction, based on Eq. 3, is approximately 30% of the total sliding friction. This indicates that phonon effects are the dominant mechanisms in sliding friction for the system.

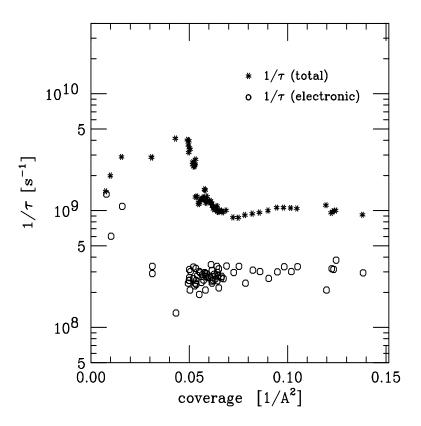


Figure 2: Typical values for the inverse of the electronic and total slip times  $\tau_{eh}$  and  $\tau$  for Xe monolayers adsorbed on Ag(111).

The approximately 25% increase in sliding friction from the first monolayer to the second monolayer, also observed in previous studies [12], is unaccompanied by a corresponding increase in electronic friction, which is consistent with the fact that electronic friction arises from interfacial electronic interactions and is therefore determined primarily by the first layer. On the other hand, phonon friction associated with a bilayer is expected to be significantly greater than that associated with a monolayer due to the presence of more vibrational modes into which mechanical energy can be dissipated [13]. Because of large uncertainties in the data at very low coverages, we are careful not to make any conclusions in this region.

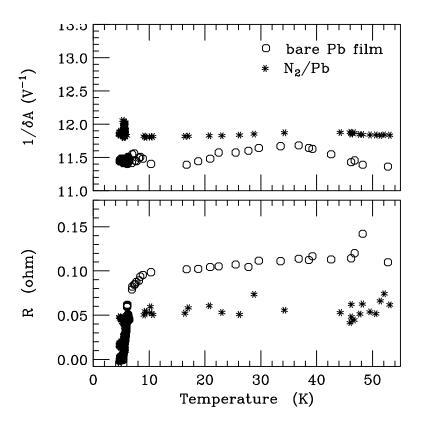


Figure 3: Inverse amplitude shift and resistance versus temperature for bare and nitrogen-covered lead films.

#### 4. SUPERCONDUCTIVITY MEASUREMENTS

Another approach to determine the electronic contribution to the total sliding friction is to see how the slip time  $\tau$  changes when the metal substrate undergoes phase transition to a superconducting state, in which case the electronic contributions should be significantly altered, with  $1/\tau_{eh} \to 0$ , leaving only phonon contributions.

Experiments were carried out on the system  $N_2/Pb$ . Pb thin films are known to go superconducting as high as 7.5K. We evaporated 200nm-thick lead films onto quartz crystals for QCM and electrical resistivity measurements. Evaporation was done at room temperature and at base pressure  $10^{-8}$  Torr. The samples were then transferred to a gas-dosing chamber where measurements can be carried out down to 4.2K.

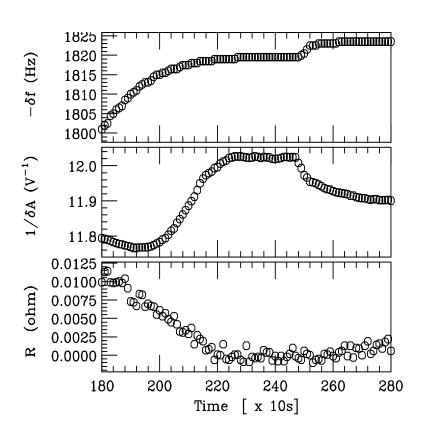


Figure 4: QCM and electrical resistivity data for  $N_2/Pb$  during the transition of the Pb film to a superconducting state. (Data are plotted against time for clarity.)

Fig. 3 shows QCM data for both bare and nitrogen-covered Pb films. Resistivity data is also included to show that the samples did go superconducting around 5K. As expected, the QCM inverse amplitude data for the gas-covered metal film is shifted up relative to that for the bare sample, indicating energy dissipation between adsorbed layer and substrate. As the lead film goes superconducting, an increase in energy dissipation is observed for the nitrogen-covered sample, shown in fig. 4, but not for the bare substrate. This additional energy dissipation can be attributed to an increase in slippage between film and substrate as interfacial friction levels go down due to the disappearance of electronic contributions.

Comparing the relative dissipation levels due to the total sliding friction (before

onset of superconductivity) and the remaining phonon friction (after the phase transition), we estimate phonon contributions to sliding friction to be about 35%. This indicates that electronic effects dominate over phonon mechanisms for this case.

#### 5. DISCUSSION

We have carried out electrical resistivity and QCM measurements on the systems Xe/Ag(111) and N/Pb to determine the relative contribution of electronic and phonon dissipative mechanisms to sliding friction. Our results show the proportion of electronic contributions to be around 30% for Xe/Ag and 65% for  $N_2/Pb$ . While there is a striking difference in the dominance of electronic effects in the two systems, it is clear that electronic mechanisms are a significant source of energy dissipation.

## ACKNOWLEDGMENTS

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